Chapter III.15

Plasma wakefield acceleration and the AWAKE experiment at CERN

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The high gradient of plasma wakefield acceleration makes this technology very interesting for reducing the size (and cost) for future linear colliders. The idea is to use plasma to convert the transverse electric field of a drive bunch into a longitudinal electric field in the plasma. The more energy is available, the longer (distance-wise) these plasma wakefields can be driven.

AWAKE is an international Collaboration, consisting of 22 institutes. In AWAKE many general issues are studied, which are relevant for concepts that are based on plasma wakefield acceleration.

III.15.1 Introduction to plasma wakefield acceleration

The next generation of particle physics experiments demands accelerators capable of reaching higher energies to address unresolved questions beyond the Standard Model. Traditional accelerators have utilized conventional radiofrequency (RF) cavities for over a century with great success. However, these RF cavities face inherent limitations in terms of the accelerating gradients they can achieve, typically maxing out around 100 MV/m. For instance, accelerators like the LHC operate with gradients around 5 MV/m, the ILC with 35 MV/m, and CLIC reaches up to 100 MV/m. In metallic structures, pushing the electric fields beyond a certain threshold results in surface breakdown, leading to electric discharges that can damage the accelerating equipment.

In contrast, plasmas, which are already ionized or "broken down", can sustain electric fields up to three orders of magnitude higher than conventional RF structures. Plasma wakefield acceleration, therefore, presents a highly promising technology due to its potential for achieving much higher accelerating gradients, offering a pathway to significantly reduce the size and cost of future linear colliders.

Plasma wakefield acceleration is an advanced particle acceleration technique that exploits the collective behavior of plasma, the fourth state of matter. Plasma is an ionized gas composed of free electrons and positive ions, which, in equilibrium, is quasi-neutral, meaning that it has no net charge. In plasma wakefield acceleration, plasma is used to generate powerful electric fields, or wakefields, that can accelerate charged particles to very high energies over short distances.

III.15.1.1 Concept and mechanism

The seminal idea of plasma wakefield acceleration was proposed by T. Tajima and J. Dawson in 1979 [1]. They suggested using a plasma to transform the transverse forces of a high-energy beam of particles,

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called the “drive beam”, into longitudinal electric fields within the plasma. These fields could then be harnessed to accelerate a second beam of particles, known as the “trailing” or “witness” beam. The drive beam can either be a charged particle beam, such as electrons or protons, where the space-charge field causes the charge separation in plasma, or a high-intensity laser beam, which relies on the ponderomotive force. In the case of the AWAKE experiment at CERN, protons are used as the drive beam.

As the relativistic drive beam propagates through the plasma, it perturbs the distribution of plasma electrons. This disturbance pushes plasma electrons outward, away from the beam path, leaving behind positively charged ions. The displaced electrons then rush back due to the attractive force of the ions, leading to plasma oscillations. These oscillations generate both longitudinal and transverse electric fields—collectively referred to as the plasma wakefield. The plasma wakefield can accelerate the trailing bunch if it is placed in the correct phase of the oscillation (see Fig. III.15.1). This phase alignment is crucial for effective acceleration.

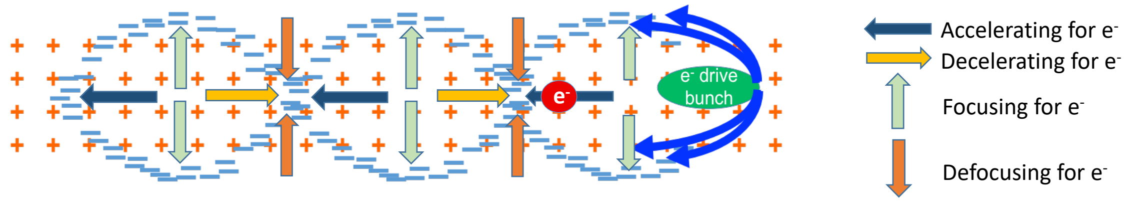

Fig. III.15.1: Simplified scheme of the plasma wakefield acceleration principle.

III.15.1.2 Plasma oscillation frequency and wavelength

The oscillation angular frequency of the plasma, ω_{pe}, depends on the plasma density n_{pe}, and is given by

$$\omega_{pe} = \sqrt{\frac{n_{pe}e^2}{m_e \epsilon_0}} \quad , \tag{III.15.1}$$

where e is the electron charge, m_e is the mass of the electron, and ϵ_0 is the permittivity of free space. The wavelength of the plasma oscillation, λ_{pe}, is inversely related to the plasma frequency ω_{pe}, and can be expressed as

$$\lambda_{pe} = \frac{2\pi c}{\omega_{pe}} \quad , \tag{III.15.2}$$

where c is the speed of light. For AWAKE, which operates with a typical plasma density of $n_{pe} \approx 7 \times 10^{14}\,\mathrm{cm}^{-3}$, the corresponding plasma wavelength is on the order of 1 mm. This relatively short wavelength allows the formation of wakefields at the millimeter scale, which is much smaller than traditional accelerator structures.

III.15.1.3 Accelerating gradient and wavebreaking field

One of the primary advantages of plasma wakefield acceleration is the extremely high accelerating gradients it can achieve, far surpassing those possible with conventional RF accelerators. The strength of the electric field generated by the plasma wake is approximately equal to the "wavebreaking" field, E_{WB}, which represents the maximum electric field sustainable by the plasma before the wave breaks. The wavebreaking field is given by

$$E_{\mathrm{WB}} \approx \frac{m_e c \omega_{pe}}{e} \quad . \tag{III.15.3}$$

For the plasma density of $n_{pe} = 7 \times 10^{14}\,\mathrm{cm}^{-3}$, in the AWAKE experiment the wavebreaking field is approximately 2.5 GV/m. In contrast, for laser-driven plasma wakefields with much higher plasma densities ($n_{pe} \approx 7 \times 10^{17}\,\mathrm{cm}^{-3}$), the wavebreaking field can reach up to 80 GV/m, making this technology highly attractive for compact accelerators.

III.15.1.4 Linear regimes

When the drive beam density n_b is much smaller than the plasma density n_{pe}, linear theory can be used to describe the plasma wakefield acceleration. The linear regime offers a simpler framework for analytical solutions, making it a useful tool for understanding the fundamental principles of plasma-based acceleration. In linear theory the wakefields excited by the bunch oscillates sinusoidally with the frequency determined by the plasma density. The strength of the accelerating field increases proportionally to the number of particles in the drive bunch divided by the plasma wavelength. However, the phase and amplitude of the wakefields generated by different types of particles (e.g., electrons versus protons) are opposite in phase but equal in magnitude.

The optimal conditions for wakefield acceleration occur when the parameters $k_{pe}\sigma_z \approx \sqrt{2}$ and $k_{pe}\sigma_r \leq 1$, where $k_{pe} = \omega_{pe}/c$ is the plasma wave number, σ_z is the longitudinal r.m.s.bunch length, and σ_r is the transverse r.m.s. bunch size. For example, in AWAKE, the proton drive bunch has a transverse size of $\sigma_z = 200\,\mu$m, so the ideal plasma density is approximately 7×10^{14} cm^{-3}, according to these equations.

For effective particle acceleration, the witness bunch must be positioned in the part of the wakefield where both longitudinal and transverse forces are favorable. Since these fields are 90° out of phase, only a quarter of the plasma wavelength provides the ideal conditions for simultaneous focusing and acceleration.

Increasing the driver strength to $n_b/n_{pe} \lesssim 1$ for beam drivers increases the accelerating gradient and allows for higher witness beam charge, while the field structure remains approximately sinusoidal. This regime is referred to as the quasi-linear regime. If the driver strength is further increased, the wakefield enters the fully non-linear regime, where a kinetic description of the plasma becomes necessary.

III.15.2 Proton drive beams in plasma wakefield acceleration

Numerous experiments employing laser pulses as drivers have demonstrated that wakefields in the range of tens of GV/m and higher can be sustained. The highest energy achieved so far is 7.8 GeV in a single 20 cm plasma stage [2]. Comparable accelerating gradients have also been attained using electron bunches as drivers. In particular, a single bunch of electrons driving wakefields produced energy gains of 42 GeV for some particles [3], while a witness bunch was accelerated by 9 GeV per particle [4]. However, both laser pulses and electron bunches are limited by their relatively low stored energy at the order of tens of joules per bunch, prompting ongoing research into multi-stage acceleration systems to reach the energy levels required for particle physics applications. But in order to achieve this level of energy gain, the approaches would require multiple stages, posing challenges such as precise timing, matching, and alignment between stages.

AWAKE is the only facility in the world that utilizes a proton bunch as the drive beam for plasma wakefield acceleration. The use of a proton beam offers significant advantages due to its high energy content. The proton bunch from CERN's Super Proton Synchrotron (SPS) carries 19 kJ of energy per bunch, and an LHC proton bunch contains as much as 300 kJ. This high energy opens up the potential for reaching TeV-scale electron energies in a single stage.

Simulations suggest that existing proton beams could accelerate electrons to energy levels sufficient for high-energy physics applications. For example, an SPS proton beam at 450 GeV could accelerate electrons to 200 GeV, and an LHC proton beam could drive electrons to 3 TeV. This makes proton-driven plasma wakefield acceleration an attractive option for future particle physics accelerators aiming at the energy frontier.

Self-modulation of the proton bunch

One of the critical requirements for generating high-amplitude wakefields is that the drive beam's bunch length should be comparable to the plasma wavelength. For typical plasma densities in AWAKE, the plasma wavelength is on the order of 1 mm. However, current proton bunches, such as those from the SPS, have much longer lengths ($\sigma_z = 6$–10 cm), which would typically produce only small wakefield amplitudes.

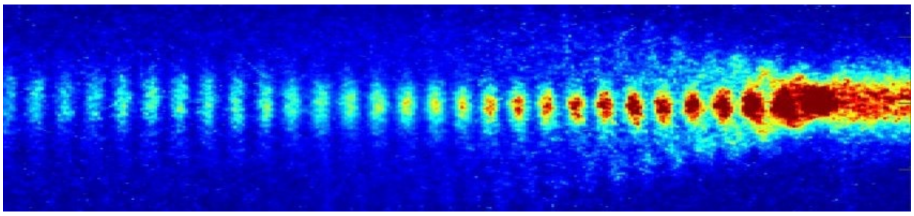

Fig. III.15.2: Proton bunch train formed in plasma by the self-modulation instability. The micro-bunches are separated by the plasma wavelength and propagate to the right (Credit: AWAKE Collaboration).

To overcome this, AWAKE relies on the self-modulation instability (SMI) of the proton bunch [5]. SMI is a process in which the wakefields driven by the long proton bunch act back on the bunch itself, modulating its transverse distribution and breaking it up into a train of micro-bunches. These micro-bunches are separated by the plasma wavelength and resonantly drive strong wakefields (see Fig. III.15.2). Without seeding, the instability grows from noise or imperfections in the proton bunch distribution, leading to variations in amplitude and timing. However, by applying an external seed wakefield, the timing and amplitude of the self-modulation process become well-defined and reproducible. This seeding process ensures that the micro-bunches remain in phase with the plasma oscillations, resulting in a coherent and high-amplitude wakefield that can be used for particle acceleration.

The combination of high-energy proton drive beams and the self-modulation instability opens the door for immediate use of the SPS proton beam in the AWAKE experiment.

III.15.3 The AWAKE experiment at CERN

The Advanced WAKEfield Experiment, AWAKE [6, 7], at CERN is an international collaboration involving 22 institutes and is the first facility, which uses a proton beam to drive wakefields in plasma, enabling the acceleration of externally injected electrons to GeV energy levels. The experiment is located 60 meters underground, upstream of the former CERN Neutrinos to Gran Sasso (CNGS) target area (see Fig. III.15.3).

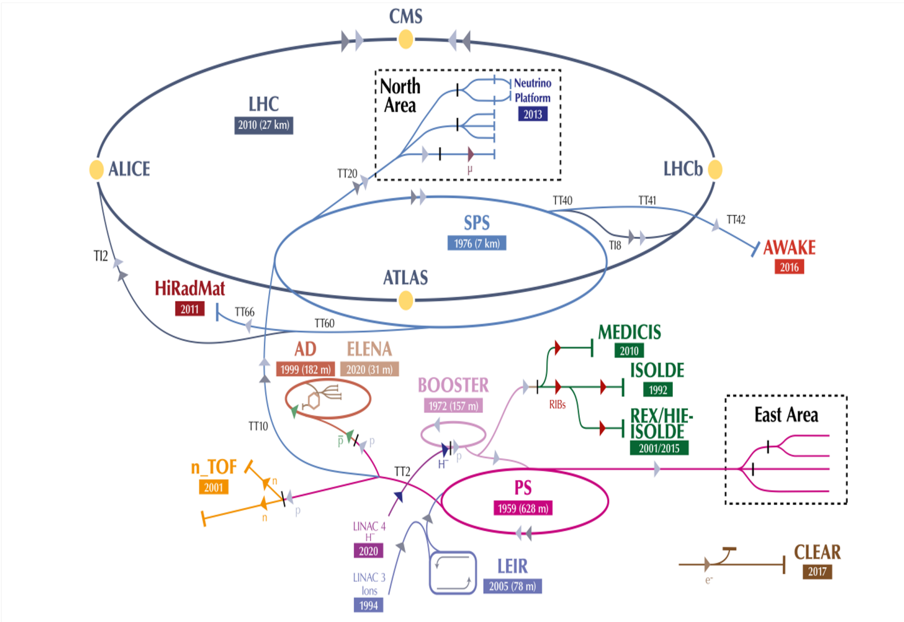

Fig. III.15.3: CERN accelerator complex.

III.15.3.1 Current experimental setup

In AWAKE, a 400 GeV proton bunch, 6 cm in length, is extracted from the SPS and directed into a 10-meter-long plasma source filled with rubidium vapor. The plasma source is heated to around 200°C to maintain the required plasma electron density, which ranges from 0.5×10^{14} to 10^{15} electrons per cm^3.

A 120-fs laser pulse with an energy of approximately 100 mJ and a wavelength of 780 nm is synchronized with the proton bunch and creates a relativistic ionization front (RIF), ionizing the rubidium vapor and generating the plasma. The fast onset of this ionization process seeds the self-modulation of the proton bunch. The alignment between the proton bunch and plasma is inherently ensured due to this method, providing a stable and reliable means of generating the wakefields.

Once the proton bunch exits the plasma source, it passes through an optical transition radiation (OTR) screen, which generates time-resolved images of the proton bunch's charge density. These images are captured by a streak camera to visualize the modulation. Additionally, an RF photo-injector, based on an S-band structure, is used to inject 18 MeV electrons into the plasma. After passing through the plasma, the energy spectrum of the accelerated electrons is analyzed using a magnetic spectrometer located downstream of the plasma source.

III.15.3.2 AWAKE Run 1: proof-of-concept

AWAKE Run 1, conducted between 2016 and 2018, served as a proof-of-concept experiment, successfully demonstrating the feasibility of proton-driven plasma wakefield acceleration. During this phase, it was shown that a highly relativistic, high-energy proton bunch could be effectively modulated in plasma through the self-modulation instability. This modulation led to the resonant excitation of strong wakefields, providing a crucial mechanism for particle acceleration. The experiment also demonstrated that by seeding the self-modulation process with an ionizing laser pulse, the resulting wakefield excitation was phase-stable, ensuring consistent acceleration conditions [8–10].

Another key achievement during Run 1 was the acceleration of externally injected electrons to multi-GeV energies [11]. Moreover, it was found that introducing a positive gradient in plasma density along the length of the plasma source resulted in a 20% increase in energy gain for the accelerated electrons, highlighting the potential for further optimization of the system. Figure III.15.4 illustrates the results of these key milestones.

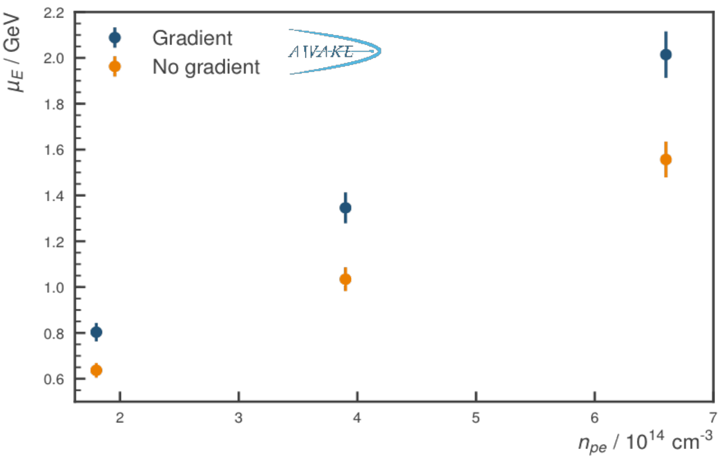

Fig. III.15.4: Measurement of the highest peak energies μ_E of the accelerated electrons achieved at different plasma densities n_{pe}, with and without a gradient in the plasma density [11].

III.15.3.3 AWAKE Run 2: advancing proton-driven plasma wakefield acceleration

Building on the successful proof-of-concept results from AWAKE Run 1, the AWAKE collaboration has developed an ambitious and well-defined program for Run 2 [12]. Run 2 started in 2021, is staged in four phases and will last over several years.

The primary objective of Run 2 is to achieve electron acceleration with energy gains in the range of 0.4 to 1 GeV per meter, while maintaining the beam quality, characterized by the normalized emittance to be between 2 to 30 mm-mrad and a relative energy spread of a few percent. Additionally, AWAKE aims to develop scalable plasma sources that can extend to hundreds of meters, a critical step toward realizing this technology for future particle physics applications.

Once the technical milestones of Run 2 are demonstrated, the AWAKE acceleration scheme could be used in a range of experiments, including the production of electron beams with energies between 40 and 200 GeV for fixed-target experiments, such as searches for new phenomena associated with dark matter.

III.15.3.3.1 Experimental program and setup

The experimental layout for Run 2 incorporates several key changes from Run 1, particularly the introduction of two distinct plasma sources. The first plasma source serves as the "self-modulator," where the proton bunch undergoes seeded self-modulation, generating and maintaining high-amplitude wakefields. The demonstration of this is the first milestone of Run 2.

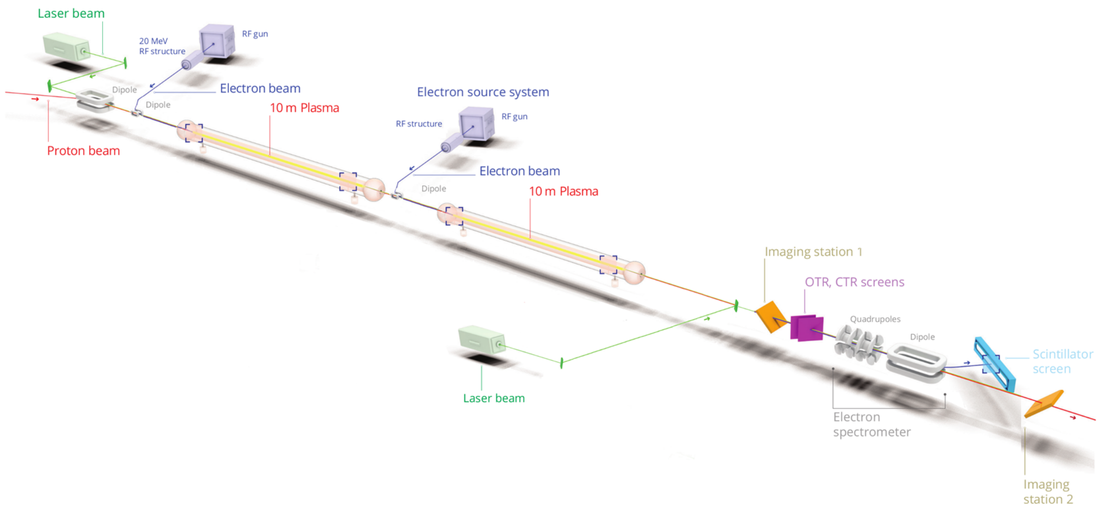

Fig. III.15.5: Layout of AWAKE Run 2. The first plasma source (left) is the self-modulator, the second one (right) the accelerator plasma (Credit: AWAKE Collaboration).

The second plasma source is the "accelerator" source, where electrons are injected and accelerated, while controlling the beam quality. With this layout AWAKE aims to achieve the second milestone: the acceleration of electrons in the range of 4 to 10 GeV in 10 m plasma, a low electron energy spread (5–8%) with an accelerated bunch charge of approximately 100 pC and a normalized emittance of 2–30 mm-mrad. To meet these goals, beam loading is required to flatten the wakefield and to control the emittance growth. This necessitates the use of a new electron beam system featuring a radiofrequency (RF) photo-injector and two X-band accelerating structures. The beam transfer line is meticulously designed to inject 150 MeV electrons into the plasma with a beam size of 5.75 µm and normalized emittance of 2 mm-mrad. A prototype of the new electron source has already been installed and successfully commissioned at CERN's CTF2 facility, validating the new design.

Additional significant upgrades to the experimental setup to support the goals of Run 2 include upgraded laser systems for both plasma sources and the electron injector, enhanced beam instrumentation such as proton beam position monitors with 10 µm resolution.

The third milestone refers to demonstrating the scalability of the acceleration process. In the last phase of Run 2, it is planned to replace the second plasma source with a new plasma technology scalable to lengths of tens to hundreds of meters, which will be crucial for achieving high-energy electron beams. Two plasma source technologies are currently under development: helicon plasma sources (HPS) and discharge plasma sources (DPS).

- Helicon Plasma Sources (HPS): by stacking units of radiofrequency antennas and magnetic field coils, these sources can be extended to greater lengths while maintaining uniform density.
- Discharge Plasma Sources (DPS): in this configuration, multiple plasma sources are stacked, with one high-voltage cathode in the center and grounded electrodes at either end, allowing for scalability while ensuring uniformity.

Both are being tested for scalability and uniformity at a dedicated CERN laboratory, with the aim of extending these sources to lengths of ten meters or more. In addition diagnostic techniques to monitor and optimize these plasma sources are developed.

A 10-meter prototype of a discharge plasma source was installed, commissioned and operated successfully in the AWAKE facility during a three-week proton run in 2023.

The successful demonstration of scalable plasma sources will be a major milestone for Run 2, paving the way for future high-energy physics applications.

III.15.3.3.2 Experimental results of AWAKE Run 2

The first milestone of Run 2 is the completion of the self-modulator, a crucial component that reshapes the long proton bunch into a series of micro-bunches, enabling efficient wakefield generation. The measurements can be done in the existing AWAKE facility as described in Section III.15.3.1. The measurement program started in 2021 and the completion of this milestone is anticipated by the end of 2024, with the demonstration of the self-modulation process structured in two experimental phases. First results are very promising.

III.15.3.3.2.1 Phase 1: self-modulation control (2021–2022)

The first phase, completed in 2022, demonstrated that wakefields driven by the entire proton bunch could consistently produce reproducible and tunable timing. This result is particularly significant given that the experiment relies on the self-modulation instability, which is inherently unstable and difficult to predict. However, AWAKE successfully showed that this instability could be controlled and optimized, allowing for reproducible results. In this experiment, the self-modulation instability is seeded by wakefields generated by a preceding electron bunch. This electron bunch, injected ahead of the proton bunch, initiates the wakefields in the plasma, which imprint themselves on the proton bunch, facilitating the development of a well-defined micro-bunch train [13]. It is important to note that the electron bunch is not used for acceleration purposes but solely for triggering the self-modulation of the proton bunch.

III.15.3.3.2.2 Phase 2: sustaining high-amplitude wakefields over long distances (2023–2024)

The second phase of the experiment focuses on demonstrating that strong wakefields can be sustained over long distances. Theoretical simulations indicate that optimizing the plasma density profile—by introducing a step or gradient in the density, for instance—can enhance the wakefield strength and sustain it over extended distances. This enhancement is critical for maintaining the accelerating fields required for high-energy electron acceleration.

To this aim a new rubidium plasma source was installed in 2023, which was developed by MPP Munich and WDL, UK. This new source is shown in Fig. III.15.6 and includes several features: individually controllable heating sections allow to set a density step along the plasma. Ten view-ports along the 10 m long vapour source make it possible to measure the plasma light induced by the wakefields. Movable plungers were installed every meter along the vapour source which allows to vary the plasma length.

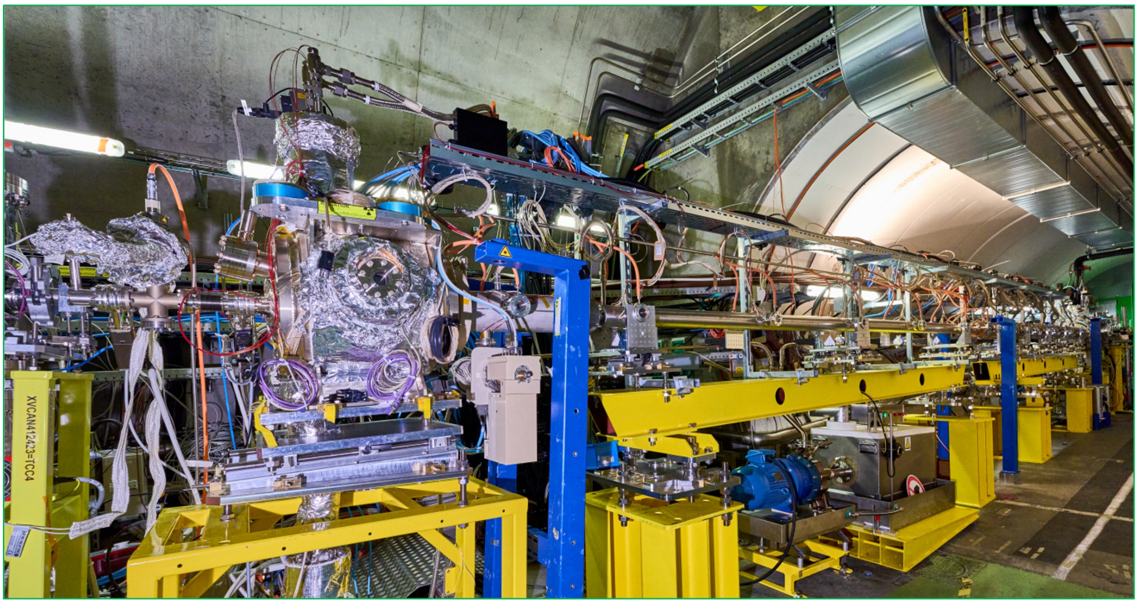

Fig. III.15.6: 10 m-long rubidium vapor source in AWAKE (Credit: CERN).

Preliminary measurements conducted in 2023 and 2024 have provided promising results. Introducing steps in the plasma density profile has already led to significant energy gains in externally injected electrons, validating the predictions from numerical simulations. Ongoing experimental efforts throughout 2024 will focus on further optimizing the self-modulator, with the goal of completing this crucial stage of the experiment.

III.15.3.3.3 Next steps

To accommodate the additional equipment and infrastructure required for Run 2 acceleration experiment, the AWAKE facility will undergo major modifications, with works starting in 2025. This includes dismantling the CERN Neutrino Gran Sasso (CNGS) target area, which currently occupies a 100-meter tunnel section downstream of the AWAKE experimental facility. This expansion will provide the necessary space for the installation of the second plasma source and the associated electron injection systems.

The modifications are scheduled in such a way that the AWAKE facility is ready for the acceleration experiment in line with first protons after CERN's Long Shutdown, LS3, in 2028.

III.15.4 Outlook

Once the goals of Run 2 are achieved, the AWAKE experiment will be well-positioned to propose its plasma wakefield acceleration technology for first particle physics applications [12].

For example SPS protons can be used to accelerate electrons in plasma up to 200 GeV with an intensity of 10^9 electrons/bunch. First applications with these electrons could investigate dark photon searches in beam dump mode, allowing for better sensitivity than current experiments. High-energy electron bunches could also explore non-linear QED in electron-photon collisions, where the low repetition rate of proton bunches is not a major limitation. TeV-range electrons produced with LHC proton bunches could be used for lower-luminosity electron-proton or electron-ion collisions. In summary, plasma wakefield acceleration offers a promising pathway to next-generation accelerators with reduced size and cost compared to conventional technologies.

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